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Impacts of sea level rise in the New York City metropolitan area

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Abstract

The greater New York City region, with over 2400 km of shoreline, will be vulnerable to accelerated sea level rise (SLR) due to anticipated climate warming. Accelerated SLR would exacerbate historic trends of beach erosion and attrition of highly productive coastal salt marshes. Coastal populations in the region have swelled by around 17% (av.) and over 100% in some localities between 1960 and 1995. The coastal zone will thus be increasingly at risk to episodic flood events superimposed on a more gradual rise in mean sea level. Projections of sea level rise based on a suite of climate change scenarios suggest that sea levels will rise by 18–60 cm by the 2050s, and 24–108 cm by the 2080s over late 20th century levels. The return period of the 100-yr storm flood could be reduced to 19–68 years, on average, by the 2050s, and 4–60 years by the 2080s. Around 50% of the land surface of salt marsh islands have disappeared in Jamaica Bay since 1900. While losses prior to stricter environmental protection starting in 1972 can largely be attributed to anthropogenic activities, such as landfilling, dredging, and urbanization, further investigation is needed to explain more recent shrinkage. Given projected rates of SLR, and plausible accretion rates, these wetlands may not keep pace with SLR beyond several decades, resulting in severe loss.

Keywords: sea level rise; climate change; impacts

1. Introduction

Anticipated climate changes will greatly amplify risks to coastal populations. Globally, approximately 400 million people live within 20 m of sea level and within 20 km of a coast (Small et al., 2000). By the end of the century, increases in sea level rise of two to five times the present rates could lead to inundation of low-lying coastal regions, more frequent flooding episodes, and worsening beach erosion (IPCC, 1996a,b).

The greater New York City metropolitan area covers a 33,670 km^2 area, with 19.6 million inhabitants (of which 7.3 million reside in New York City; Fig. 1). Coastal populations in the New York, New Jersey, Connecticut area have grown by around 17% between 1960 and 1995, with seven coastal counties displaying growth rates exceeding 100% (Culliton, 1998)[1]. High-rise residential complexes are sprouting at water's edge in Jersey City, Hoboken, and Edge-

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1 Coastal counties are those located entirely or partially within the nation's coastal watersheds.

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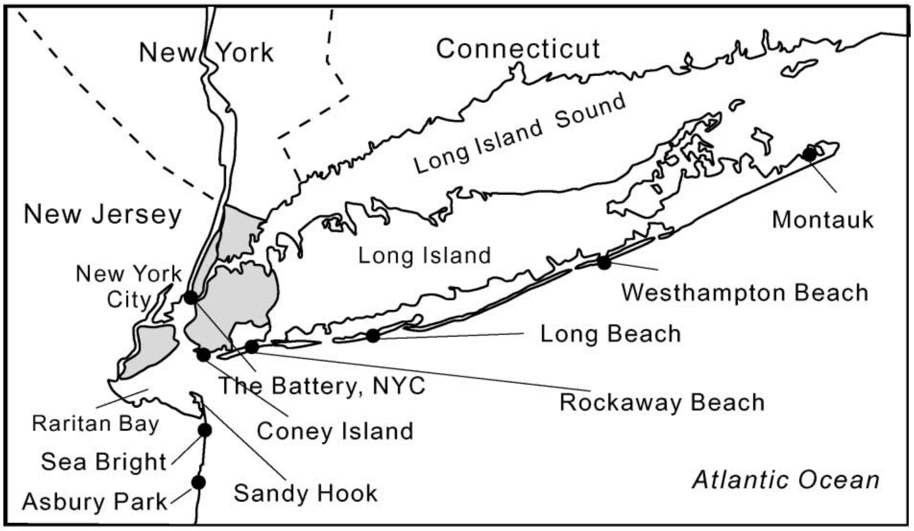

Fig. 1. Index map of study site locations.

water, NJ (Garbarine, 1999) and in lower Manhattan. New houses are being built on the dunes of the Hamptons, eastern Long Island, where many expensive homes were lost during severe winter storms in the winter of 1992–1993 (Fig. 2; Maier, 1998).

With close to 2400 km of shoreline, the region's development has been intimately tied to the sea. Four out of five of the New York City boroughs are located on islands. More than 2000 bridges and tunnels connect these islands and the mainland. Most area rail and tunnel entrance points and airports lie at elevations of 3 m or less (U.S. ACOE/FEMA/NWS, 1995). Flood levels of only 0.30–0.61 m above that which occurred during a December 1992 storm could have produced massive inundation and loss of life. Rising sea levels would make such flooding much more commonplace.

Beaches and other open coastal areas represent a prime recreational resource, which offers the large urban population of the MEC region relief from the summer heat, swimming, fishing, boating, and other leisure activities. As the population continues to grow and additional land is converted to higher density urban uses, less opportunity remains to expand existing public parks and beaches.

Scattered enclaves of coastal wetland ecosystems remain in the New York City metropolitan region. The Gateway National Recreation Area, established in 1972, represents a key ecological resource in an urban setting. It includes the wetlands of Jamaica Bay Wildlife Refuge, as well as recreational beaches on Staten Island, Breezy Point, NY, and Sandy Hook, NJ (Tanacredi and Badger, 1995). However, a large fraction of the original tidal wetlands of Jamaica Bay has been lost to historic infrastructure development (see Section 4.7).

This paper presents the findings of the Coastal Zone Sector of the Metropolitan East Coast (MEC)[2] region, prepared for the US National Assessment of Potential Climate Change Impacts. We investigate potential impacts of climate change on sea level rise, coastal flooding, and erosion in the MEC region and how these natural processes interact with increasing urbanization and land-use changes.

A suite of sea level projections is prepared for a number of plausible scenarios of regional climate change. Estimates are given of future coastal flood heights, return intervals, and increases in sand volumes for beach nourishment under these scenarios at selected case study sites (Fig. 1). Preliminary measurements of reduction in salt marsh area are presented. Implications of these findings for coastal management and ecological resources are also discussed.

[2] The Metropolitan East Coast (MEC) region encompasses the greater metropolitan New York City area, including adjacent portions of the northern New Jersey and southwestern Connecticut shorelines.

2. Current regional coastal hazards

Current coastal hazards include long-term sea level rise, shoreline erosion, flooding due to tropical and extratropical storms, and wetland losses.

2.1. Sea level trends

Mean global sea level has been increasing by 1–2.5 mm/yr, for the last 150 years, with 1.8 mm/yr considered the "best estimate" (Warrick et al., 1996; Gornitz, 1995a). This is the most rapid rate within the last few thousand years (Varekamp and Thomas, 1998; Gornitz, 1995b) and is probably linked to the 20th century global warming of nearly 0.5 °C (IPCC, 1996a).

Sea level has been rising along the US East Coast since the end of the last glaciation. Although deglaciation ended over 6000 years ago, sea level has continued to change due to the earth's delayed viscoelastic response to the redistribution of mass on its surface following removal of the ice (i.e., glacial isostatic changes). These sea level changes are spatially non-uniform over time scales of thousands of years to the present (Peltier, 1999).

The MEC region lies at the southern end of the Wisconsinan ice sheet, within the zone of the collapsed forebulge. This region had been upwarped over 20,000 years ago, while land to the north was depressed beneath the weight of the ice. As the land formerly under ice has isostatically rebounded (the area of glacial rebound now lies north of the St. Lawrence Valley), the Atlantic Coast south of the Canadian Maritime Provinces has subsided. Geophysical models have been used to filter these crustal motions from tide-gauge data in the eastern US (Peltier, 1999; Davis and Mitrovica, 1996).

Tide gauges measure *relative* sea level change, which includes glacial isostatic and other geologic signals, in addition to the more recent global sea level signal (Gornitz, 1995b). Late Holocene sea level proxies (e.g., mollusks, corals, peats, woods, etc.) can be used to derive a long-term sea level curve which includes these geologic trends. Subtraction of long-term trends from the recent sea level data leaves the climate-related *absolute* sea level change. The average absolute sea level-rise for eastern North America is around 1.3 mm/yr (Gornitz, 1995b, 1999, 2000).

At present, the rate of relative sea level rise in the MEC region varies between 2.20 mm/yr (Port Jefferson, Long Island) and 3.85 mm/yr (Sandy Hook, NJ, Table 1). In New York City, the rate is 2.73 mm/yr (Table 1). These values lie above the estimated global mean SLR, because of ongoing regional subsidence, but vary slightly from place to place due to various local factors.

2.2. Coastal erosion

Over 70% of the world's sandy beaches are retreating (Bird, 1985). In the MEC region, beaches and barrier islands are narrowing or shifting landward, in part due to ongoing sea level rise and land subsidence. Accelerated sea level rise may intensify the rate and extent of coastal erosion. While sea level rise is an important factor, beach erosion is frequently intensified by human activities, such as trapping of silt and sand in upstream reservoirs, disruption of longshore drift by groins and breakwaters, and sand mining. Examples of such effects in the MEC region are presented below.

2.2.1. Historical erosion trends—Long Island

Long Island formed from glacial outwash plains, stream deposits, and moraines, at the end of the last glaciation 18,000 years ago. During the post-glacial marine transgression, glacial sands and gravels were eroded and redeposited into ridges and swales on the inner continental shelf and onshore. Barrier islands have migrated landward and upward more or less continuously during the Holocene by "rolling over,"

Table 1
Relative sea level trends—New York, Connecticut, New Jersey tri-state region

Station	Latitude	Longitude	Relative sea level rise (mm/yr)
New London, CT	41°22′ N	72°06′ W	2.10
Bridgeport, CT	41°10′ N	73°11′ W	2.57
Montauk, NY	*41°03′ N*	*71°58′ W*	*2.27*
Pt. Jefferson, NY	*40°57′ N*	*73°05′ W*	*2.20*
Willets Pt., NY	*40°48′ N*	*73°47′ W*	*2.30*
New York City, NY	*40°42′ N*	*74°01′ W*	*2.73*
Sandy Hook, NJ	*40°28′ N*	*74°01′ W*	*3.85*
Atlantic City, NJ	39°21′ N	74°25′ W	3.97

Stations lying within the Metro East Coast region are set in italics.

i.e., through dune overwash and inlet formation. The present barriers are geologically young—not more than a few thousand years old, although the ancestral islands lay lower and seaward of their present positions (Leatherman and Allen, 1985).

The south shore of Long Island is now flanked by a string of barrier beaches and islands extending from the Rockaways in the west to Southampton in the east. Headland beaches and bluffs constitute the remainder of the eastern Long Island shoreline toward Montauk Point. Littoral currents move sand from Montauk Point westward toward New York City, except where intercepted by "hard" structures, such as groins or jetties.

Most of the southern Long Island coastline has been eroding between 1834 and 1979, on average (Leatherman and Allen, 1985). One exception is the western end of Fire Island, which has accreted seaward, especially since the construction of jetties at the Fire Island Inlet in 1941. Major coastal erosion also followed construction of jetties at the Moriches and Shinnecock Inlets (1952–1954), and groins near Westhampton in the late 1960s, which intercepted the westward longshore drift (Kana, 1995).

2.2.2. Historical erosion trends—northern New Jersey

The northern New Jersey ocean shoreline extends from Asbury Park in the south to Sandy Hook in the north. The historic mean erosion rate for the period 1836–1985 was 0.8 m/yr (Gorman and Reed, 1989). The coast south of Sandy Hook has generally retreated over the 149-yr period, except between 1932 and 1953. The Sandy Hook spit, now part of the Gateway National Recreation Area, accreted landward prior to 1900, but eroded severely between 1900 and 1953, and has stabilized since. Between 1953 and 1985, the shoreline of northern New Jersey has remained fairly stable, except for two erosion hotspots, around Asbury Park and north of Sea Bright.

Major beach nourishment projects were undertaken in Sea Bright and Asbury in the early 1990s (Bocamazo, 1991), and at Sandy Hook during the 1980s and early 1990s (Psuty and Namikas, 1991). A seawall/groin complex near Sea Bright has significantly reduced northward longshore sediment flow to Sandy Hook and steepened the nearshore slope. These factors have enhanced natural erosion due to the long-term sea level rise (3.85 mm/yr at Sandy Hook). These adverse conditions necessitate periodic beach replenishment (Psuty and Namikas, 1991).

The Raritan Bay estuarine coast has receded landward at an average rate of 2.4 m/yr, between 1836 and 1855/1857 (Jackson, 1996). The shoreline expanded seaward by 0.53 m/yr, between 1855/1857 and 1932/1934, due to extensive development, and construction of bulkheads, seawalls, and groins designed to protect the shoreline. The 1932/1934–1957 period saw a slight erosion (or negative) trend of 0.32 m/yr. Since 1957, the shoreline has remained relatively stable, except for some growth near beach nourishment projects.

The historic regional tendency toward coastal erosion, particularly following major storms as shown below, must be periodically reversed by expensive beach replenishment projects. A number of such projects have been undertaken by the US Army Corps of Engineers in New Jersey and along the south shore of Long Island (Table 2, Valverde et al., 1999).

2.3. Coastal storms

2.3.1. Nor'easters (extratropical cyclones)

Nor'easters (extratropical cyclones), most prevalent between January and March, are responsible for major coastal flooding and beach erosion along the US East Coast. Although their wind speeds are lower than in hurricanes, they cause considerable damage because of their greater areal expanse and duration over several tidal cycles at a particular location (Davis and Dolan, 1993; Dolan and Davis, 1994).

Table 2
Cumulative beach nourishment costs for case study sites

Location	Time period	Adjusted cost (1996 $)
Coney Island	1923–1995	$25,220,000
Rockaway Beach	1926–1996	$134,334,956
Lido Beach (Long Beach)	1962	$1,492,010
Westhampton Beach	1962–1996	$47,167,821
Sea Bright–Monmouth Beach	1963	$8,212,536
Sandy Hook–Deal (includes Sea Bright)	1995–1996	$35,973,000
Total		$252,410,323

Sources: Duke University Program for the Study of Developed Shorelines, (Valverde et al., 1999).

Storm frequencies along the East Coast over the last 50 years peaked in the late 1960s, diminished in the 1970s, and picked up again in the early 1990s (Dolan and Davis, 1994). However, there has been no discernible increase in either the number or severity of storms over this period. Twentieth century tide-gauge records from Atlantic City, NJ and Charleston, SC, show no statistically significant trends in either the number or duration of storm surge events, after removing tidal components and long-term sea level rise (Zhang et al., 1997). The secular increase in coastal flooding is largely a consequence of the regional sea level rise during this period, and illustrates how rising ocean levels are likely to exacerbate storm impacts.

Significant nor'easters within the last 40 years include the "Ash Wednesday" storm (March 6–7, 1962), the Halloween storm (October 31, 1991), and two other powerful coastal storms on December 11–12, 1992 and March 13–14, 1993. The "Ash Wednesday" storm, with flood levels over 2.1 m at the Battery, lower Manhattan, was particularly destructive over the mid-Atlantic states because it lasted for five tidal cycles. However, the December 1992 storm produced some of the worst flooding seen in the New York metropolitan area in 40 years. The water level at the Battery tide-gauge peaked at 2.6 m above the National Geodetic Vertical Datum of 1929 (2.4 m above mean sea level; U.S. ACOE/FEMA/NWS, 1995), when tides were already above normal due to the full moon. Flooding of lower Manhattan, together with near hurricane-force wind gusts led to the almost complete shutdown of the metropolitan New York transportation system, as well as evacuation of many seaside communities in New Jersey, Connecticut, and Long Island (New York Times, December 12, 1992; Storm Data, December 1992).

The December 1992 storm revealed the vulnerability of the metropolitan New York–New Jersey–Connecticut transportation systems to major nor'easters and hurricanes. Most area rail and tunnel points of entry, and airports lie at elevations of 3 m or less (U.S. ACOE/FEMA/NWS, 1995). This elevation represents a critical threshold. Flood levels of only 0.30–0.61 m above those of the December 1992 storm could have resulted in massive inundation and loss of life.

The vulnerability of the regional transportation system to flooding was demonstrated again on Aug. 26, 1999, after 6.4–10.2 cm of rain fell on the New York metropolitan area, nearly paralyzing the system (New York Times, August 27, 1999). With future sea level rise, even less powerful storms could inflict considerable damage (see Section 4.3).

2.3.2. Hurricanes

Hurricanes are major tropical cyclones or low-pressure systems whose destructiveness derives from very high winds (minimum wind speeds of at least 119 km/h), flooding due to high storm surge and waves, and heavy rainfall. The storm surge is a dome of water produced by low barometric pressure and strong wind shear, particularly on the right side of the low-pressure system. The height of the surge is amplified if it coincides with the astronomical tide. Waves add to the flooding.

The frequency and intensity of Atlantic basin hurricanes show multidecadal variations, but no secular trends between 1944 and 1996 (Landsea et al., 1999). A period of many severe hurricanes (Saffir–Simpson categories 3–5; Table 3) in the 1940s–1960s was followed by relative quiescence during the 1970s–early 1990s and greater activity since the late 1990s.

Atlantic hurricanes are affected by the El Niño–Southern Oscillation. During the El Niño phase, an increase in tropical vertical shear increases due to stronger upper-atmosphere westerly winds inhibiting the development and growth of tropical Atlantic hurricanes. Therefore, Atlantic cyclones are 36% more frequent and 6% more intense during the La Niña phase of ENSO than during an El Niño (Landsea et al., 1999). The probability of sustaining at least $1 billion in damages is 77% during a La Niña year, as compared to only 32% in an El Niño year, and 48% in a "neutral" year (Pielke and Landsea, 1999).

Table 3
The Saffir–Simpson hurricane scale

The Saffir–Simpson scale				
Category	Central pressure (mbar)	Winds (m/s)	Surge (m)	Damage
1	≥ 980	32–42	1.4	minimal
2	965–979	43–49	2.1	moderate
3	945–964	50–58	3.2	extensive
4	920–944	59–69	4.7	extreme
5	< 920	> 69	>5.5	disaster

While hurricanes are much less frequent than nor'easters in the Northeast, they can be even more destructive. At least nine hurricanes have struck the metropolitan New York City region within the last 200 years, including major ones in 1938, 1893, and 1821 (Coch, 1994). Effects include severe coastal flooding, damage and destruction of beachfront property, severe beach erosion, downed power lines and power outages, and disruption of normal transportation.

The worst natural disaster to strike the northeastern United States was the hurricane of September 21, 1938, which claimed almost 700 lives and injured several thousands more. This storm struck with little warning. A wall of water 7.6–10.7 m high (surge plus wave) swept away protective barrier dunes and buildings on the shores of eastern Long Island, eastern Connecticut, and Rhode Island (Ludlum, 1988). The August, 1893 hurricane completely destroyed Hog Island, a barrier island that once existed seaward of Rockaway Beach (Onishi, 1997; Fig. 1).

The right angle bend between the New Jersey and Long Island coasts funnel surge waters toward the apex—the New York City harbor. Surge waters also pile up at the western end of Long Island Sound. Maximum surge levels for a category 3 hurricane (179–209 km/h winds, Table 3) moving along a worst-case storm track west of New York City could reach 7.6 m above the National Geodetic Vertical Datum (7.4 m above mean sea level); at JFK airport, based on the SLOSH numerical model projections (U.S. ACOE/FEMA/NWS, 1995). Other locations around the New York metropolitan area could experience surge levels of up to 4.75–7.3 m. These figures exclude tides and waves.

2.4. Wetland losses

Many scattered parcels of coastal wetlands remain in the New York metropolitan area. In particular, Jamaica Bay Wildlife Refuge, Gateway National Recreation Area, encompasses a number of salt marshes, home to a wide variety of aquatic and avian species (Tanacredi and Badger, 1995). However, a large fraction of the original tidal wetlands of Jamaica Bay have disappeared due to historic landfill and draining. Salt marshes covered an estimated 6550 ha in 1900 (Englebright, 1975). By 1970, only around 1620 hectares of saltmarshes remained. Although protected since 1972, the remaining tidal wetlands within the boundaries of Gateway National Recreation Area were still shrinking (Section 4.7), in part due to ongoing sea level rise and other factors.

3. Methodology

A plausible suite of climate change scenarios are applied to the investigation of sea level rise impacts on selected coastal localities in New York City, Long Island, and northern New Jersey. Future coastal flood heights, return intervals, and increases in sand volumes for beach nourishment under these scenarios are calculated using US Army Corps of Engineers models.

Relevant data sets include sea level observations, meteorological data, historic shoreline data, US Geological Survey 7.5' Digital Elevation Models, aerial photography, geology. Thematic maps produced by the Geographic Information Systems lab, CIESIN, at Lamont–Doherty Earth Observatory, Columbia University show topography, population density, household income levels, and housing values. These maps are overlaid on sea level and flood data to assess areas, populations, and assets at risk.

3.1. Sea level rise

Sea level rise for the MEC region is calculated from historical tide-gauge data (Spencer and Woodworth, 1993; US data: , http://www.opsd.nos.noaa.gov) and several global climate model (GCM) simulations. Sea level rise scenarios are based on an extrapolation of current sea level trends and on the following GCMs recommended by the US National Assessment of Potential Climate Change Impacts: the Canadian Centre for Climate Modelling and Analysis (CCCMA) (Boer et al., in press) and the United Kingdom Hadley Centre (Johns et al., 1997).

Climate model outputs are adjusted for local land subsidence. The local subsidence rate is derived by subtracting the relative sea level rise at each tide-gauge station from the regional absolute mean sea level trend (Gornitz, 1995a,b, 1999, 2000). The difference between decadal mean subsidence (2000s, 2010s,... 2090s) and that of the base period (1961–

1990) is then added to the projected sea level rise for each GCM scenario, for the corresponding decade. Sea level projections are for the GCM grid cell(s) enclosing New York City and its environs.

The following scenarios are used in this study:

(1) *Current trend*. The current trend is the least-squares linear fit through the annual means of historic sea level from tide-gauge data. Mean annual sea levels are averaged in 10-yr intervals starting in 1961, to minimize effects of interannual variations.

(2) *CCGG*. The CCCMA first-generation coupled model (CGCM1) transient climate simulation for greenhouse gas warming provides only the steric (temperature/salinity) component of sea level rise. Contributions from mountain glaciers and ice sheets are calculated using static sensitivities: 0.063 cm/yr/°C (glaciers), 0.03 cm/yr/°C (Greenland), and − 0.03 cm/yr/°C (Antarctica) (Gregory and Oerlemans, 1998).

(3) *CCGS*. The CCCMA first-generation coupled model (CGCM1) transient climate simulation for greenhouse gas warming plus sulfate aerosols. In addition to the steric component of SLR, other contributions are calculated as for CCGG, except for a static sensitivity of 0.035 cm/yr/°C for Greenland (Gregory and Oerlemans, 1998).

(4) *HCGG*. Hadley Centre HadCM2; the first of an ensemble of four greenhouse gas integrations. (The four runs differ only in the year the control integration is used to initialize the first member of the run. Differences among the four runs are relatively small—R. Goldberg, priv. comm.).

(5) *HCGS*. Hadley Centre HadCM2; the same as scenario 4, including sulfate aerosols.

3.2. Storm surges

Plots of floods levels for given return periods (i.e., 2, 5, 10, 25, 50, and 100 years) were prepared for each sea level rise scenario at each site, using the WES Implicit Flooding Model (WIFM) tidal hydrodynamic model (Butler, 1978; Butler and Sheng, 1982). WIFM solves vertically integrated dynamic, shallow-water wave equations of fluid motion, incorporating information on bathymetry, topography, wave and meteorological data in order to simulate coastal flooding. An important feature of the model is its ability to stretch the numerical grid, which allows a denser grid resolution in areas of interest.

For this study, flood heights include nor'easter and hurricane storm surges, high tide, and sea level rise. Wave heights are not included. Storm climatology is assumed to remain unchanged (flood heights are relative to the NGVD datum). Projected sea level rise for the Coney Island and Rockaway Beach study sites was based on the New York City (Battery) tide gauge; the Sea Bright/Asbury Park site was referenced to the Sandy Hook gauge; SLR for Long Beach and Westhampton were calculated by linear interpolation between the New York City and Montauk tide gauges (see Section 3.6). Average flood heights were calculated for each decade between 2000 and 2090. Maximum flood levels (surge + mean high water + sea level rise) for the 100-yr storm events were compared with flood levels during major historic storm events, such as the December 1992 nor'easter.

3.3. Shoreline movement

The shoreline's response to sea level rise is often estimated using the Bruun Rule, which states that a typical concave-upward beach profile erodes sand from the beachfront and deposits it offshore, so as to maintain constant water depth. Shoreline retreat depends on the average slope of the shore profile. Thus, from Maine to Maryland, a 1 m sea level rise would cause the beach to retreat by as much as 50–100 m.

The Bruun Rule assumes no longshore transport of sand into or out of the study area, nor does it account for washover or inlet sedimentation, two important processes shaping barrier islands. It has been modified to account for landward migration and upward growth of a barrier island ("rollover"; Dean and Maurmeyer, 1983). Other shoreline models, such as three-dimensional sediment budget analysis or dynamic approaches require detailed measurement of local parameters (NRC, 1987). The lack of this information, except at a few sites, limit the widespread applicability of these models. Alternatively, projections are made from a correlation between historical shoreline erosion trends and local sea level changes (Douglas et al., 1998).

The Bruun Rule remains widely used in spite of the above-cited limitations, and is adopted here to estimate shoreline changes at the case study sites, with no sand replenishment. The Bruun Rule can be stated mathematically as:

$$S = (A * B)/d$$

where:

- S Shoreline movement
- A Sea level rise
- d Maximum depth of beach profile, measured from the berm elevation for each project location to the estimated depth of closure
- B Horizontal length of the profile, measured from the beginning of the berm to the intersection with the estimated depth of closure

The depth of closure is taken as the minimum water depth at which no significantly measurable change occurs in bottom depth. It is often erroneously interpreted to mean the depth at which no sediment moves in deeper water. "Closure" is a somewhat ambiguous term in that it can vary, depending on waves and other hydrodynamic forces. Depth of closure at our study sites was based on measured beach profiles taken perpendicular to the shore (Appendix A).

The annual shoreline translation due to sea level rise was calculated from the Bruun Rule and converted to a volumetric change, using the height of the beach profile and the length along the shore.

3.4. Beach nourishment

Sand renourishment projects are undertaken periodically at many locations to counteract the tendency toward shoreline erosion (see Sections 2.2.1 and 2.2.2). The borrow sand comes from offshore sand bars, usually within several kilometers of the beach, at depths of around 10–20 m below present mean sea level. The sand is closely matched with the original beach sand, in terms of mean grain size and overall size distribution. Adjustments in placement volumes are made to compensate for remaining differences in grain size composition.

The US Army Corps of Engineers methodology to estimate sand volumes needed to maintain a beach employs physical characteristics such as measured beach profiles, the average profile depth, and length of shoreline in the project. Sand losses are computed for historic rates (i.e., "Current trends") of sea level rise. Also considered are losses due to long-term erosion and storm-induced erosion over the life of the project (regional project lifetimes range between 25 and 50 years, see Appendix A). The required sand volume is the sum of the volumes for each of these factors. These processes inherently interact with each other. Yet, by separating them, quantifying the results individually and then summing them, one obtains an upper bound estimate of expected renourishment requirements. Such a high estimate provides an adequate safety margin to ensure the maintenance of the project design.

The standard Army Corps procedure has been modified in several ways for this study. Projected shoreline retreat is calculated from the Bruun Rule, using our sea level rise scenarios. Long-term erosion losses are based on measurements of beach profiles and volumetric changes. Storm-related losses are determined from damage by a storm event with 50% probability of occurring during the time between renourishment episodes, using the SBEACH model (Larson and Kraus, 1989), (SBEACH is an empirically based numerical model, used to predict storm-induced beach erosion, as well as bar formation and movement). Increasing flood heights due to projected sea level rise over this time are also factored into the calculation.

Changes in volumes of beach sand renourishment are tabulated for selected time intervals. Beach replenishment due to sea level rise is compared with that from historic erosion trends and storms for these selected periods.

3.5. Socioeconomic data

Maps of population densities, average housing values, and household income for the 1995 TIGER Census Tracts were overlaid on 5-ft (1.52 m) contour plots, using US Geological Survey 7.5 min Digital Elevation Model (DEM) data for the case study sites (described below). Horizontal accuracy of the topographic data is within a centimeter (root-mean-square-error), vertical accuracy is within 1 m. The flood risk zone is defined as land lying within the present 100-yr flood zone. We describe the expansion of this zone inland with sea level rise.

3.6. Case study sites

Case study sites differ in degrees of urbanization and biogeophysical characteristics. Nearly all sites are located in high to very high coastal vulnerability classes (Thieler and Hammar-Klose, 1999). Localities (other than the Battery and Jamaica Bay) lie within boundaries of US Army Corps of Engineers beach nourishment projects (Appendix A), which are designed to reduce storm damage. Army Corps projects include an initial construction component, as well as scheduled renourishment fill operations. Storm surge elevations, shoreline erosion, and beach nourishment requirements for the given sea level rise scenarios are presented for the following sites:

- The Battery, New York City, NY[3]
- Coney Island, Brooklyn, NY
- Rockaway Beach, Queens, NY
- Long Beach, Long Island, NY
- Westhampton Beach, Long Island, NY
- Sea Bright–Manasquan, NJ

3.6.1. The Battery, New York City, NY

Lower Manhattan covers high-density prime commercial real estate in the heart of the New York City financial district, residential areas, such as Battery Park City, and major tourist attractions, such as historic Battery Park, and the South Street Seaport. Battery Park City and the Seaport area have been constructed on landfill over the years. Most of the waterfront is bulkheaded and protected by a low sea wall. Portions of this area have been under water during major storms, such as the 1992 nor'easter (see above). Important transportation infrastructure vulnerable to flooding includes a number of roadways, bridge, tunnel, and subway entrances (U.S. ACOE/FEMA/NWS, 1995). The tide-gauge, located at the southern tip of Manhattan, has been in operation since 1856.

3.6.2. Coney Island

Coney Island is representative of an older, high-density urban seashore neighborhood. The beach lies at the western terminus of littoral drift along the south shore of Long Island (Kana, 1995; Leatherman and Allen, 1985). Coney Island was attached to the mainland during 1870s–1920s reclamation projects. Construction of groins at Rockaway Beach, further east in the 1920s, contributed to erosion problems (Wolff, 1989). Over $25,000,000 has been spent on beach nourishment at Coney Island between 1923 and 1995 (Table 2).

The Coney Island study site covers a 4.75-km east–west stretch of shoreline. The initial phase of the Army Corps project began in October 1994–January 1995. The project is scheduled to be renourished for a period of 50 years, with periodic renourishment of approximately 757,350 m^3 of sand every 10 years.

3.6.3. Rockaway Beach

Rockaway Beach, Queens, is a barrier spit (mean elevation 1.68 m above sea level) attached to Long Island at its eastern end at Far Rockaway. The central section of the barrier is another long-established, high-density, urbanized shorefront community. Nearly the entire barrier, including densely populated areas, lies below 3.3 m. A rock jetty, built further east in the 1940s, curtailed littoral drift to the Rockaways and enhanced erosion rates (Wolff, 1989). A total of $134 million has been spent on beach replenishment between 1926 and 1996 (Table 2).

The study area covers a 10.3-km stretch of coast. This US Army Corps project was initiated in 1975–1977. It may be maintained for an additional 25 years, with beach renourishment operations scheduled every 3 years, requiring approximately 1.34 million m^3 of sand per cycle.

3.6.4. Long Beach

Long Beach, NY, is a medium- to high-density, urbanized residential community located on a barrier island, east of Rockaway Beach. "Hard" structures include a series of rock groins built in the 1950s and a jetty at Jones Inlet to the east (Wolff, 1989). Lido Beach Town and Pt. Lookout, at the eastern end of Long Beach Island, have attempted to protect and revegetate their dunes, but wave refraction around the jetty has led to further beach erosion. $1.5 million had been spent on beach nourishment in Lido Beach in 1962. A renourishment project over a 12.5-km distance is planned starting in 2002–2003, covering a 50-

[3] Sea level, surge and flood data only.

yr period. It would have a 6-yr renourishment cycle, using approximately 1.6 million m^3 of sand per cycle.

3.6.5. Westhampton Beach

Westhampton Beach is an affluent low-density residential area with prime recreational beaches. The entire barrier lies below 3 m except for a narrow strip of dunes. Private houses, beach clubs, and hotels have been built on the dunes. Historically, it has been very vulnerable to storm erosion and washover. Erosion began after stabilization of the Shinnecock Inlet further east, in 1942 (Wolff, 1994). Following extensive flooding and erosion from the "Ash Wednesday" nor'easter in 1962, a series of 15 groins were built between 1965 and 1970 to protect the shore from further damage. However, for various reasons, several additional groins and beach fill were not constructed. Overall, \$47 million have been spent between 1962 and 1996 to maintain the beach (Table 2).

The barrier was breached in two locations during the December 1992 nor'easter and around 60 homes were destroyed. The smaller, western opening—Pikes Inlet—closed in January, 1993. The larger, eastern opening—Little Pikes Inlet—developed 300 m from the westernmost groin (Fig. 2; Terchunian and Merkert, 1995). A 5.5-m-deep channel formed, allowing tidal currents to erode the inlet and carry sediments bayward, forming a tidal delta and sand spit that extended northeastward into Moriches Bay. This breach was repaired in late 1993 with sand dredged

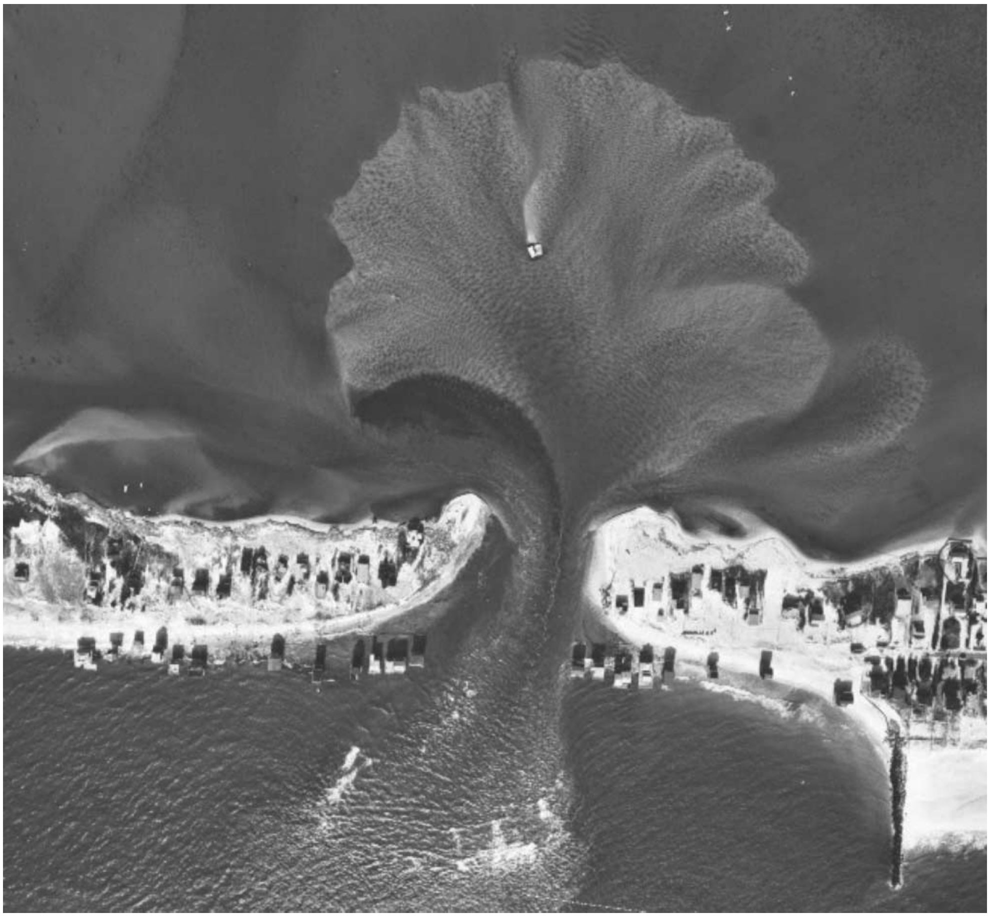

Fig. 2. Aerial view of Little Pikes inlet, Westhampton Beach, after the December 1992 nor'easter. North is up. The field of view is around 610 m across. (Source: Fred Mushacke, New York State Department of Environmental Conservation, Bureau of Marine Resources).

from offshore sources and reinforced with steel sheeting. While the presence of groin field may have contributed to the 1992 washover, this section of the barrier was already susceptible to storm damage due to lack of bayside salt marshes, sand bars, and overwash lobes (Wolff, 1994). New homes are being constructed on the site of the former breach.

The US Army Corps project, initiated in 1997, covers a stretch of 6.4 km. It is scheduled to run for a period of 30 years. The expected renourishment cycle is 3 years, using approximately 0.90 million m^3 of sand per cycle.

3.6.6. Sea Bright–Manasquan, NJ

Sea Bright, a residential community located on the southern part of the Sandy Hook spit, on the northern New Jersey shoreline, has a long history of exposure to storm and wave action. Starting in 1913, a set of 85 groins were constructed throughout the area, and in 1922, a 120-m breakwater was completed in Sea Bright. In the 1950s, a seawall was built between Sea Bright and Monmouth Beach (Gorman and Reed, 1989). By the late 1980s, the seawall had seriously deteriorated and repairs were undertaken in 1990 (Bocamazo, 1991).

Beach nourishment between 1994 and 1998 covered a 19.0 km reach between Sea Bright and Ocean Township. The project has a planned 6-yr renourishment cycle, over a 50-yr period, requiring 2.7 million m^3 of sand per cycle. Another project due south extends over 14.5 km between Asbury Park to Manasquan. It began in 1997–1999 and is expected to continue for 50 years, with periodic renourishment every 6 years, consuming 2 million m^3 of sand per cycle.

3.7. Wetland studies—Jamaica Bay Wildlife refuge

The dominant plant species of the low marsh intertidal zone is *Spartina alterniflora* (saltmarsh cordgrass) (Bertness, 1999). Other low marsh species include *Salicornia virginica* (glasswort). *Spartina patens* takes over at mean high water. *Phragmites australis* (common reed) grows in the driest regions of the high marsh zone. Frequency of tidal flooding is the major factor in determining plant species zonation. Changes in saltmarsh plant zonation over time can serve as a useful indicator of sea level rise.

Aerial photographs of selected salt marshes taken in 1959, 1976, and 1998 were analyzed to detect changes in land area. Several marshes (e.g., Yellow Bar Hassock, Black Wall Marsh, and Big Egg Marsh) were examined with stereopairs having greater than 60% overlap. Changes in landmass were calculated using standard photogrammetric techniques. Field investigations were undertaken during the summer of 1999 to study plant species composition, geomorphology, and provide ground truth checking for the remote sensing observations.

A longer timeline was obtained from digitized navigation charts and topographic maps dating back to 1899 and 1900 (Stephen McDevitt and Bob Will, US Army Corps of Engineers; David Fallon and Fred Mushacke, New York State Department of Environmental Conservation, priv. comm., March 2000). The NY State Department of Environmental Conservation map series for 1900, 1974, and 1994 was used to compared wetlands extent before and after the 1970s, when stricter environmental regulation limited landfill operations in Jamaica Bay.

4. Results

4.1. Sea level rise

The regional mean relative sea level rise for the East Coast is 2.7 ± 0.7 mm/yr; the corrected sea level rise, after removal of geologic trends, is 1.3 ± 0.7 mm/yr (Gornitz, 1995b, 1999, 2000). Tide-gauge stations within the MEC region include: New York City–the Battery, Montauk Point, Sandy Hook, Willets Point, and Port Jefferson (Table 1). Projected sea levels for these stations are reported as the decadal means of the 2020s, 2050s, and 2080s (the decadal mean is presented to minimize effects of interannual variability; Table 4).

Modest rises in sea level of 11–19 cm could occur by the 2020s at current rates (Table 4). For the GCM projections, sea levels could reach 11–30 cm. By the 2050s, sea level could rise by 18–31 cm at current rates, or could climb by 22–60 cm for the GCM projections. By the 2080s, sea level could rise by 24–42 cm, at current rates, or could exceed 1 m at some localities in the Canadian Climate Centre model. While sea levels are not expected to rise dramatically within the next 2–3 decades, the rise accelerates sharply after the 2050s, except for the "current trend" scenario (Fig. 3). Furthermore, the sea level rise trajectories diverge widely in the second half of the century.

Table 4
Sea level rise projections—Metro East Region (in cm)

Scenario	Station				
	New York City	Willets Point	Port Jefferson	Montauk	Sandy Hook
2020s					
Current trend	13.7	11.5	11.0	11.4	19.3
CCGG	24.1	21.9	21.4	21.8	29.7
CCGS	21.7	19.5	19.0	19.4	27.3
HCGG	16.1	14.0	13.5	13.8	21.7
HCGS	13.9	11.7	11.2	11.6	19.5
2050s					
Current trend	21.8	18.4	17.6	19.2	30.8
CCGG	51.1	47.7	46.9	47.5	60.1
CCGS	47.5	44.1	43.3	43.8	56.5
HCGG	32.5	29.1	28.3	28.9	41.5
HCGS	25.8	22.4	21.6	22.1	34.8
2080s					
Current trend	30.0	25.3	24.2	25.0	42.4
CCGG	95.5	90.8	89.7	90.5	107.9
CCGS	75.9	71.2	70.1	70.9	88.3
HCGG	54.4	49.7	48.6	49.4	66.7
HCGS	42.6	37.9	36.8	37.6	55.0

4.2. Coastal storms and global warming

How are the number and strengths of extratropical and tropical cyclones likely to change as the world heats up? Climate model simulations of cyclonic behavior under global warming yield contradictory results.

4.2.1. Nor'easters

Beersma et al. (1997) find a small decrease in the number of strong North Atlantic depressions (<975 h Pa) in a CO_2-doubled world, with a tendency toward a greater number of weaker storms, as compared to the present-day control simulation. Yet these differences remain small with respect to the natural variability. On the other hand, Lunkeit et al. (1996) observed an intensification of upper troposphere eddy activity—a proxy for storm tracks—and also cyclone frequency over the eastern North Atlantic and Europe, as greenhouse gas concentrations increase by 1.3%/yr. In yet another study, cyclone frequency in a doubled-CO_2 run decreases northeastward of North America and Greenland into northern Europe (Schubert et al., 1998), whereas cyclone intensity shows little change.

4.2.2. Hurricanes

Tropical cyclones are generated under conditions of sea surface temperatures >26 °C, weak vertical shear of horizontal winds, atmospheric instability, high relative humidity at lower atmospheric levels, and location a few degrees poleward of the equator (Henderson-Sellers et al., 1998). Although the area of oceans >26 °C is likely to expand as the earth warms, the minimum temperature at which tropical cyclones develop also increases by 2–3 °C. Therefore, the geographic region in which hurricanes form may not change significantly.

Henderson-Sellers et al. (1998) detect no discernable historic trends in tropical cyclone numbers, intensity, or location (see also Landsea et al., 1999). While some climate models suggest increases in the maximum potential intensity of tropical cyclones in a doubled-CO_2 climate, changes in other climatological variables may counteract these increases.

In summary, the extent to which changes in storm behavior will impact coastal regions and wetlands remains unclear. Although the intensities of weaker storms may not alter significantly, the most severe storms could become more intense and frequent, thereby causing greater damage. The frequency of storms in the Metro East Coast region could change, either as a result of an actual increase in the number of storms generated (increase in cyclogenesis), or simply due to a shift in the mean position of extratropical storm tracks (which would concurrently decrease storm frequency elsewhere).

Inasmuch as no consensus has emerged among climate models, we report changes in flood heights, storm recurrence intervals, and beach erosion trends (e.g., Figs. 4, 5 and 8), assuming that storm climatology remains unchanged, for the purposes of this assessment.

4.3. Storm surges and coastal flooding

Flood heights are presented for the 100-yr storm (combined extratropical and tropical cyclones, Fig. 4). The regional 100-yr flood levels could rise from

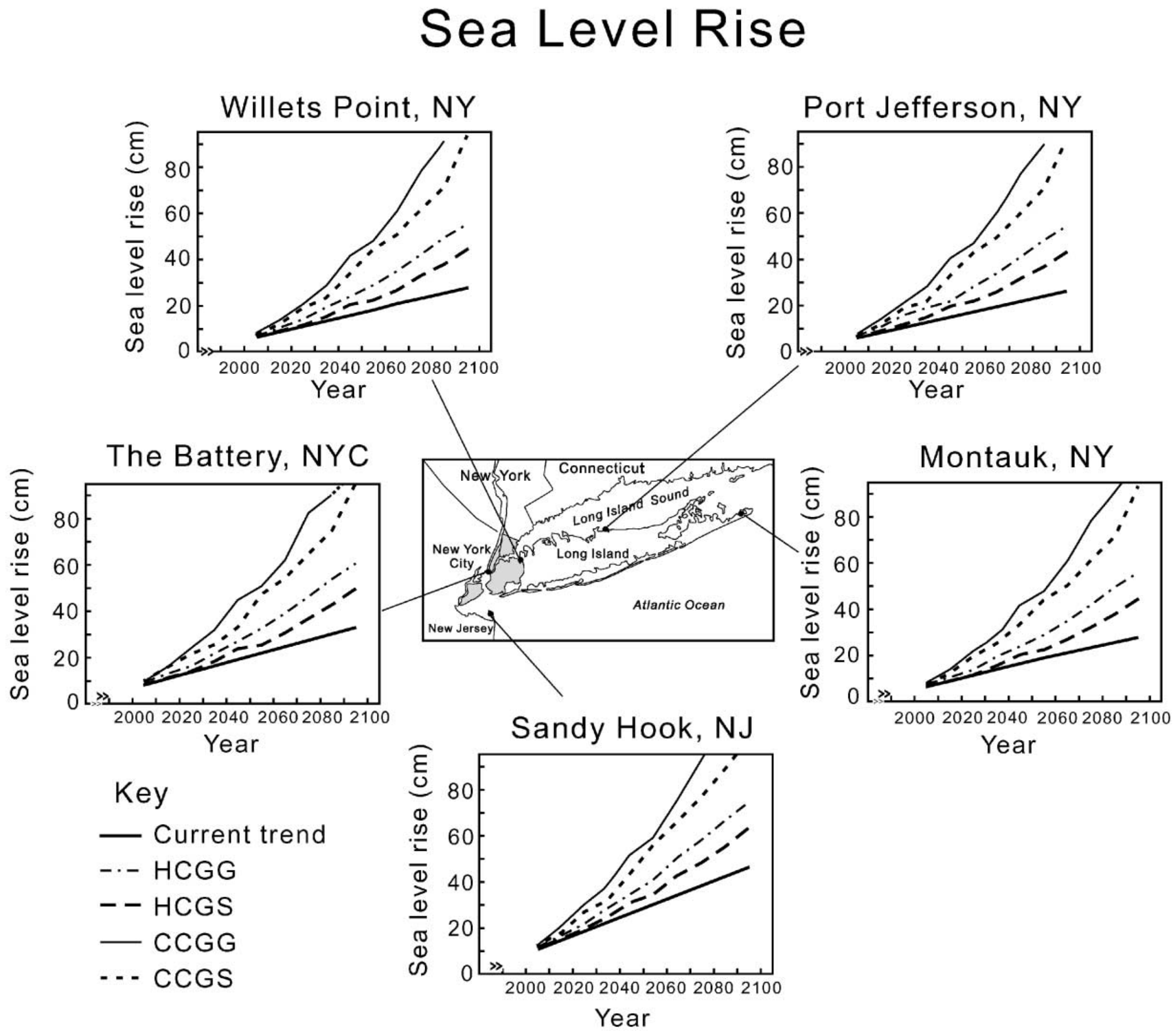

Fig. 3. Trajectories of sea level rise for the MEC region, (in centimeters).

3.0–3.5 m in the 2020s, to 3.1–3.8 m in the 2050s, and up to 4.2 m in the worst-case scenario by the 2080s (Fig. 4). These figures include high mean water, but not the additional height of waves on top of the surge.

The marked decrease in the flood return period will become a major concern to coastal residents. Among the case study sites, the likelihood of a 100-yr flood could become as frequent as once in 43 years by the 2020s, once in 19 years by the 2050s, and once in 4 years by the 2080s, on average, in the most extreme case (Fig. 5).

The current 100-yr flood height in New York City and environs is 2.96 m—very close to the area outlined by the 10-ft (3 m) contour (Fig. 6). By the 2080s, the return period for the 10-ft (3 m) flood could shrink to 5.5 years, on average, in the worst-case scenario (CCGG) and 50 years—extrapolating current trends. More frequent flooding episodes would adversely affect major transportation arteries, including highways, rail and air transportation, not to mention the viability of waterfront structures.

The projected sea level rise for the MEC region (a maximum of 48–60 cm by the 2050s and 90–108 cm

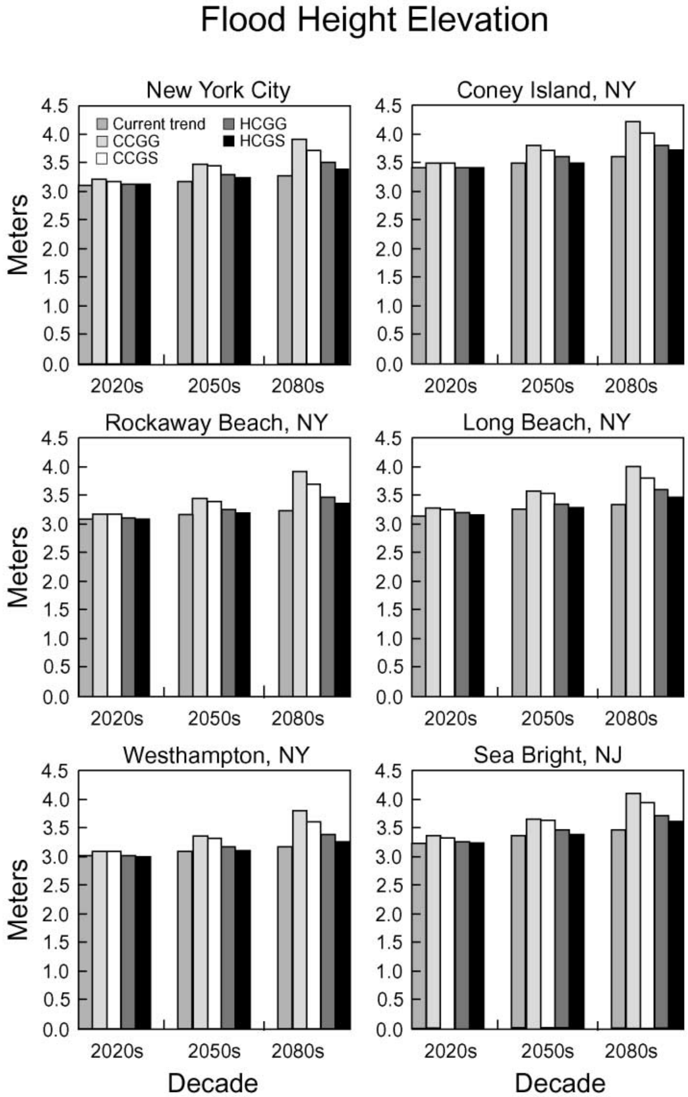

Fig. 4. 100-yr flood levels for combined extratropical and tropical cyclones, MEC region, (in meters).

by the 2080s, Table 4) lies below the 5-ft (1.5 m) contour (shown in yellow, Fig. 7a–d). Thus, only a relatively narrow coastal strip would be permanently inundated at most of the case study sites. Wetlands, however, could sustain marked reductions in area (see below).

On the other hand, areas at risk to severe flooding could expand considerably. Within two decades, the 100-yr flood zone (Fig. 4) would exceed 3 m (10 ft [3 m] contour = dark blue line; Fig. 7a–d). By the 2080s, the 100-yr flood zone could reach 3.4–4 m, within the area enclosed by the 10–15-ft (3–4.6 m) contours (light and dark blue lines). The areas at risk could embrace significant segments of lower Manhattan (Fig. 6), Coney Island (Fig. 7a), and Rockaway Beach (Fig. 7b). In addition to the entire Westhampton barrier, the inner shores of Moriches and Shinnecock Bays could also become vulnerable to flooding (Fig. 7c). The flood risk zone near Sea Bright and Asbury Park, NJ would mainly affect the immediate

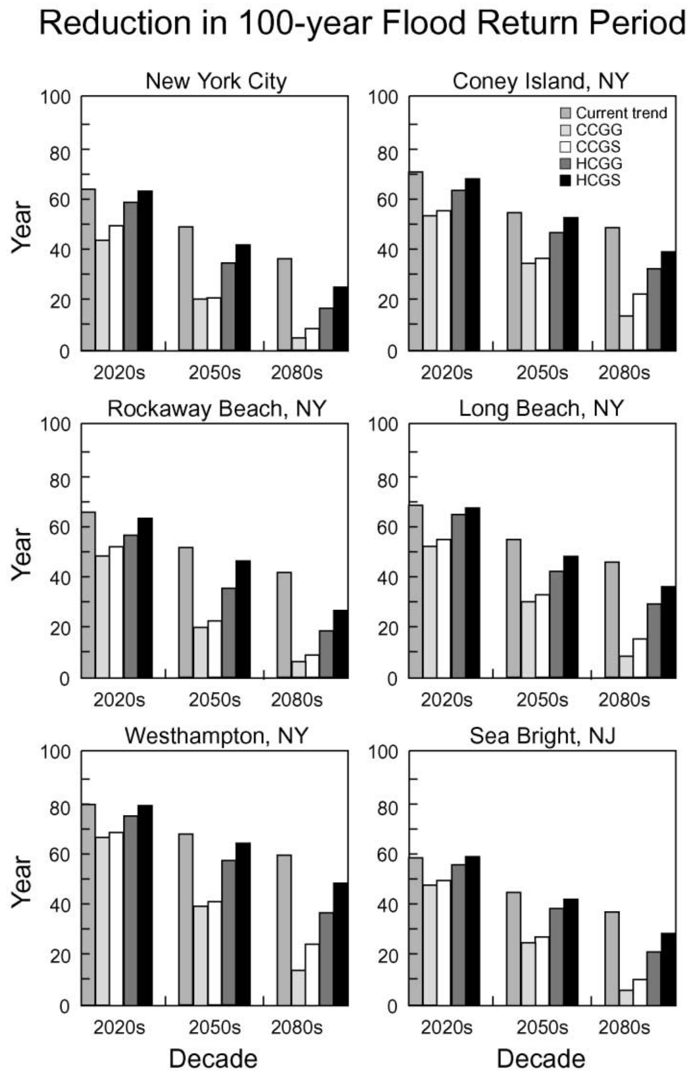

Fig. 5. Reduction in 100-yr flood return periods due to sea level rise.

shoreline, but would extend further inland along estuaries (Fig. 7d).

4.4. Shoreline changes

Fig. 8 summarizes rates of shoreline retreat due to sea level rise that would occur at the case study sites (Fig. 1), without additional sand replenishment. (The Battery in New York City is omitted here, since it is armored by seawalls). Among the sites, the Rockaway beaches shrink the most, closely followed by Asbury Park and Westhampton Beach. Coney Island beaches contract the least under all sea level rise scenarios.

These site-to-site variations reflect differences in underlying geology, geomorphology, sediment particle size distributions, beach profiles, and wave climates. But at any given locality, holding these other variables constant, erosion rates are roughly proportional to sea level rise. Thus, by the 2080s, erosion rates range

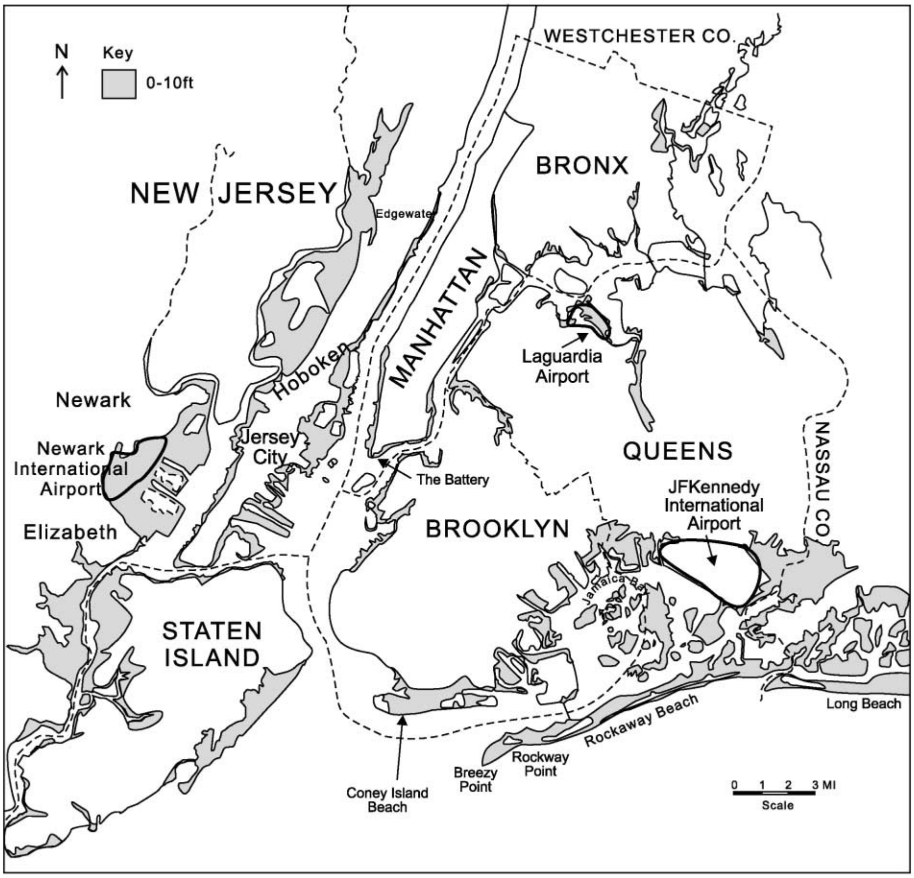

Fig. 6. Flood risk zone, New York City metropolitan area.

between 2 and 4 times above those of 2020s, and 4 to 10 times above those of the 2000s. With rising sea level and no sand replacement, Long Island and northern New Jersey beaches could move landward nearly 0.4–0.9 m/yr by the 2000s, increasing to as much as 0.85–3.6 m/yr by the 2080s (Fig. 8).

Comparison with long-term (~century) erosion trends (Leatherman et al., 2000) provides an empirical test of the Bruun Rule. The average ratio of the erosion rate based on the Bruun Rule to the rate of sea level rise for southern Long Island is 98.3, in reasonably close agreement to a ratio of 110 for historical Long Island data from sites away from nearby inlets and coastal engineering (Leatherman et al., 2000). However, the corresponding ratio for northern New Jersey is 83.1 as compared to 181 for historical data. The Bruun Rule may be a less reliable predictor of coastal erosion for the northern New Jersey sites than on Long Island because of the oversteepened offshore topography and more heavily engineered coastline in the former case (see Section 2.2.2).

4.5. Beach nourishment

In general, estimated sand volumes based on our *current trends* sea level rise scenario agree to within a few percent with values computed according to standard Army Corps methodology, over the design lifetime of the project (25–50 years; Appendix A).

Table 5(a) summarizes beach renourishment needs for our case study sites due to sea level rise over selected time intervals. At any given site, volumes of sand pumped on the beaches increase by factors of two to seven times in the 2050–2080 period relative

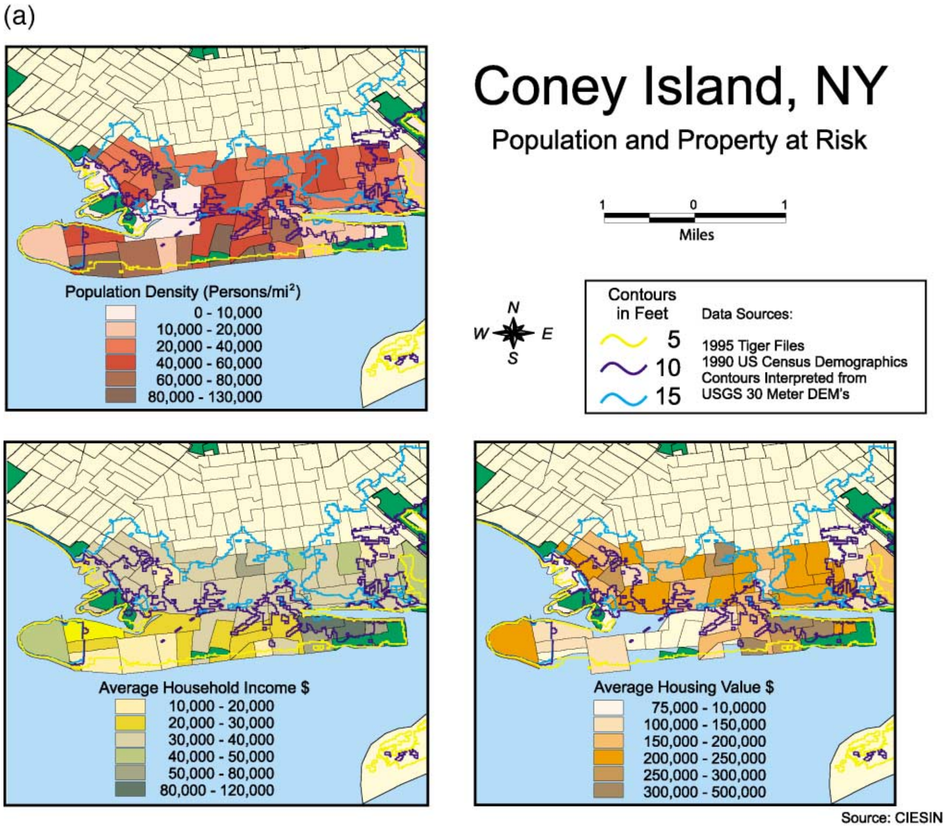

Fig. 7. (a–d) Areas vulnerable to flooding at case study sites, based on the sea level rise scenarios.

to the 2000–2020 period. Sea Bright, on the southern end of Sandy Hook with the highest rate of relative sea level rise in the region (Table 1) consumes the greatest volume of sand, among the case study sites (Table 5(a)). Sea Bright requires around twice the sand volume as Westhampton Beach (the site with the lowest sand needs) between 2000 and 2020, and two to three times as much between 2050 and 2080.

To put these figures in perspective, the additional sand needed because of SLR remains a relatively small percent of the total beach renourishment requirements from all factors (including long-term erosion, storms), until the latter half of this century. By the 2020s, the percentage due to SLR alone represents only 2.3–11.5% of the overall total (Table 5(b)), rising to as much as 18.7% by the 2050s. But after the 2050s, SLR could be responsible for a significant percentage (up to 25.7% at some localities) of the sand volume placement on beaches.

4.6. Population and assets at risk

The unavailability of high spatial resolution topographic and socioeconomic data precludes quantitative assessment of people and property at risk to SLR and flooding, at this time. However, vulnerable areas can be qualitatively outlined by overlaying topography at 5-ft (1.5 m) contour intervals with census tract data (Fig. 7a–d), together with the sea level and storm flood projections of Sections 4.1 and 4.3.

Because of the highly developed coastline within the MEC region, a large population and considerable private property and infrastructure are potentially at risk from inundation and flooding. While land lost to the sea generally occupies a relatively narrow coastal

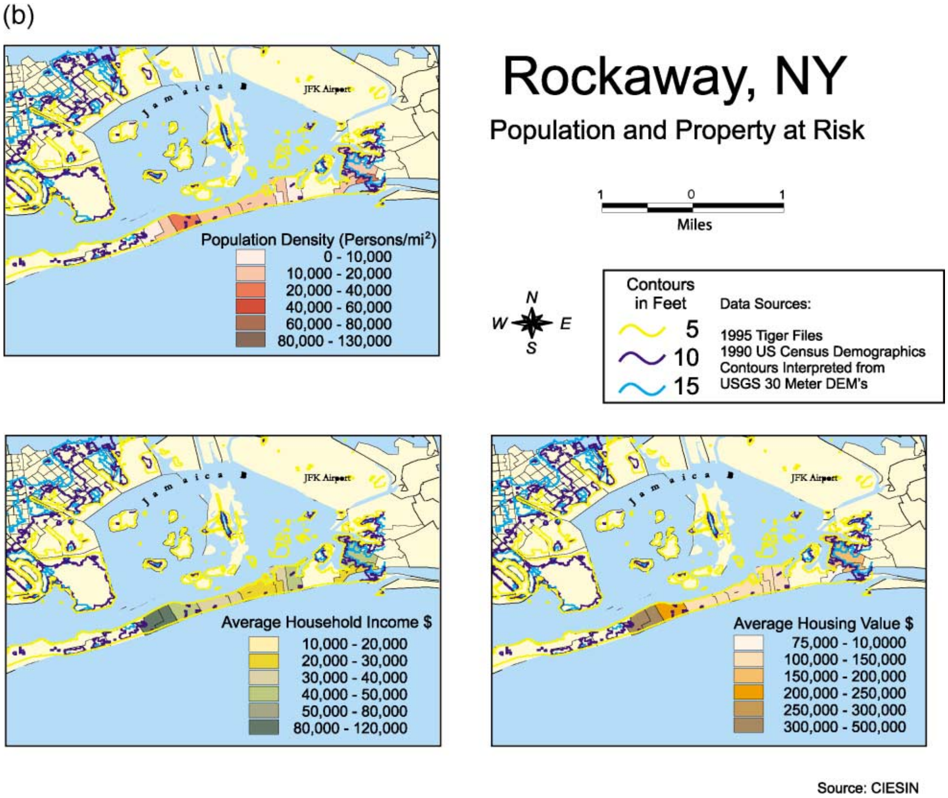

Fig. 7 (*continued*).

strip (generally below the 5-ft [1.5 m] contour, yellow line, Fig. 7a–d), flooding due to storms could periodically engulf a much greater area.

The projected 100-yr flood levels (Fig. 4) for the given SLR scenarios lie between the 10 and 15 ft (3–4.6 m) contours (Fig. 7a–d). High population densities are concentrated near the water's edge at three urban case study sites—lower Manhattan, Coney Island, and Rockaway Beach (all part of New York City). The flood risk zones cut across wide variations in income and housing values (Fig. 7a–b).

Concentration of high population densities in vulnerable areas will pose serious problems in the event of evacuation during major storms, in as much as many evacuation routes lie close to present-day storm flood levels (U.S. ACOE/FEMA/NWS, 1995). The greater frequency of severe flooding episodes affecting waterfront residences (e.g., Fig. 5) may lead to abandonment of lower floors, as in Venice, or ultimately of entire buildings.

Suburban sites, such as Westhampton, NY, Sea Bright and Asbury Park, NJ typically exhibit lower population densities and higher income levels. These land-use characteristics could make relocation to higher ground a more feasible option, if necessary, than in the highly urbanized areas.

4.7. Wetland losses

Several island salt marshes in Jamaica Bay showed apparent signs of shrinkage along their shores between 1959 and 1998 (e.g., points A and B, Yellow Bar Hassock), while tidal inlets and tributaries widened (point C and D, Fig. 9). Measurements of three island marshes indicated an estimated landmass loss of 12% over this period (Table 6(a)).

These preliminary observations were supported by data from analysis of historic maps and charts covering the entire Jamaica Bay over a longer time period by the New York State Department of Conservation. The

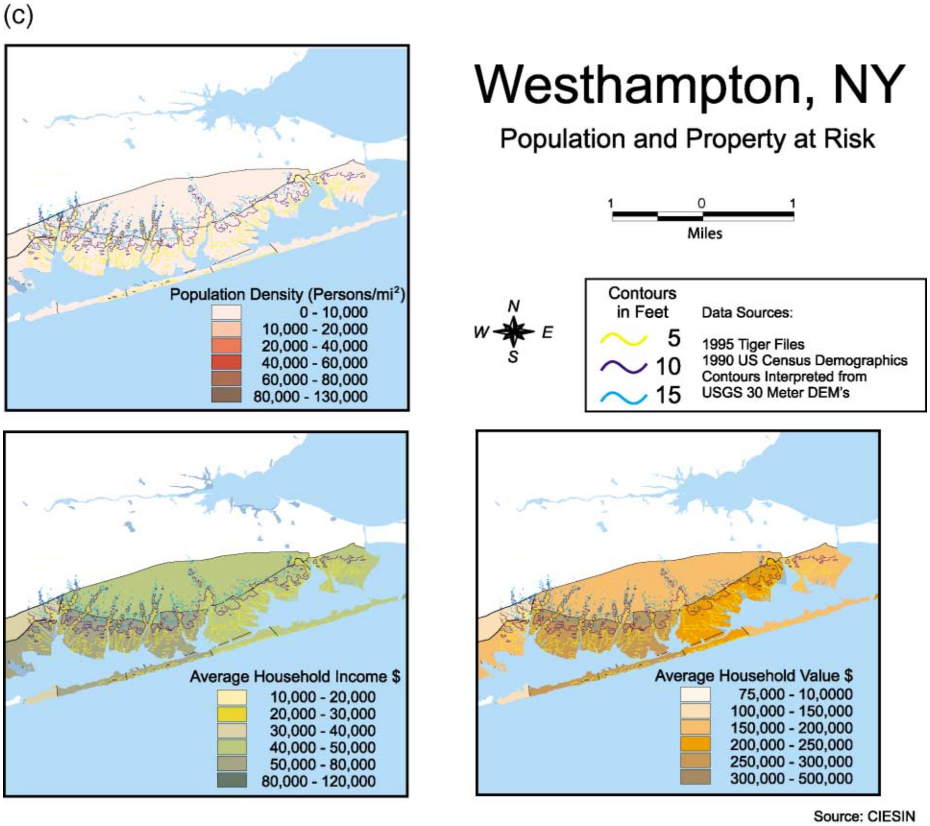

Fig. 7 (*continued*).

more comprehensive mapping survey revealed a 50% loss of island salt marsh area between 1900 and 1994 (Table 6(b)). Over 475 ha of island salt marshes disappeared between 1900 and 1974, amounting to $\sim$6.4 ha/yr. From 1974 to 1994, another 162 ha, or 8.1 ha/yr vanished (Table 6(b)). Losses during the earlier period could be largely attributed to human activities, such as landfill, dredging, or draining. Yet marshland reduction persisted, after the 1970s, in spite of stronger environmental protection.

Field studies documented evidence of recent geomorphological and biogenic deterioration. These include: (1) erosion by undermining and collapse of peat banks; (2) enlargement of holes created by biogenic activity; (3) erosion of tidal creeks; (4) enlargement of tidal pools; and (5) widespread deterioration of marsh vegetation leading to general scour and surface lowering. While erosion of the island shorelines could be attributed to wave scouring by boat wakes, the expansion of tidal pools and vegetation deterioration suggest the possibility of land inundation. Possible causes include the long-term sea level rise, insufficient sediment supply, and damage by wave action from boat wakes. But further research will be needed to verify which processes are responsible.

In view of the losses already underway, how are the Jamaica Bay saltmarsh islands likely to fare in the future? Accretion rates for Jamaica Bay are not presently available although field measurements are planned in the near future (Dr. R. Michael Erwin, USGS and University of Virginia, priv. comm., 2000). If 5 mm/yr is taken as a representative rate of accretion in Jamaica Bay, based on a literature survey (Table 7(a)), salt marshes would have difficulty keeping pace with SLR for most scenarios after the 2030s, except if current rates were to continue (Table 7(b)). Another adverse factor is the limited

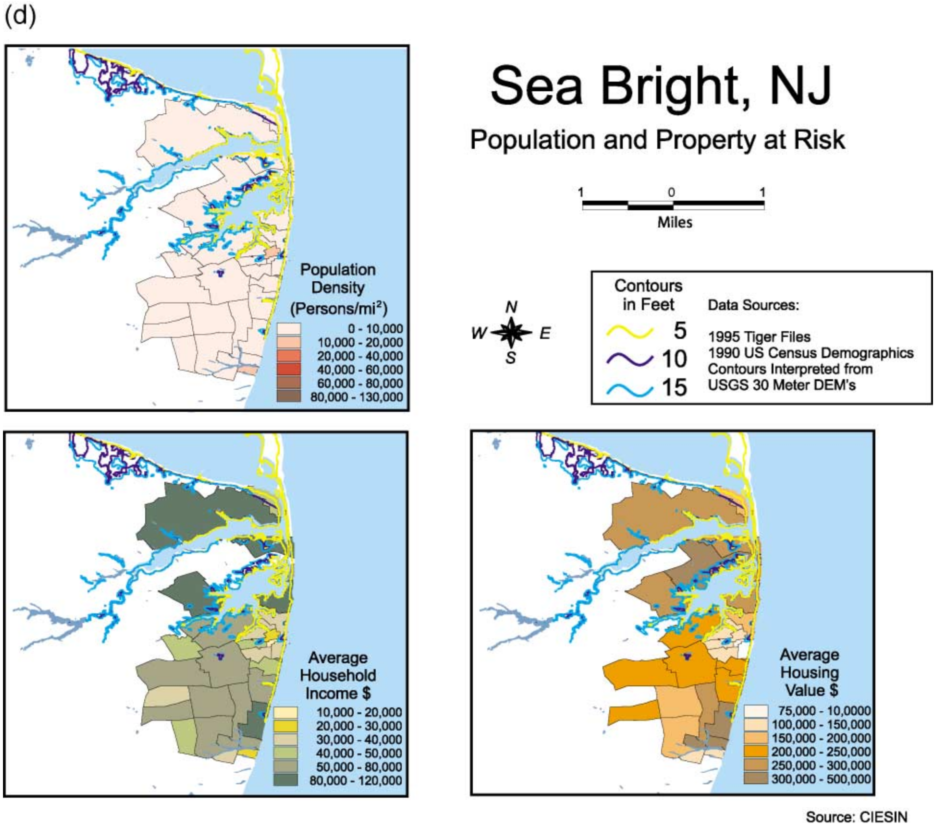

Fig. 7 (*continued*).

open space available upland for landward marsh migration.

5. Adapting to sea level rise

Strategies for coping with coastal erosion and flood damages associated with a rising sea level include defending the shoreline by means of protective structures, beach restoration, and ultimately, retreat (NRC, 1987, 1990, 1995). Even at present rates of sea level rise, most of the shoreline of the MEC region is eroding (Section 2.2). Many beaches must be artificially maintained by the US Army Corps of Engineers (Table 2).

Shoreline armoring is typically applied where substantial assets are at risk. Hard structures include seawalls, groins, jetties, and breakwaters. Seawalls and bulkheads, a common form of shore protection in urban areas, often intercept wave energy, increasing erosion at their bases, which eventually undermines them. Erosion can be reduced by placing rubble at the toe of the seawall. Groins, often built in series, intercept littoral sand moved by longshore currents, but often enhance beach erosion further downdrift if improperly placed (e.g., at Westhampton Beach). Jetties are constructed to stabilize inlets or to protect harbors. Their erosive consequences resemble those of groins (e.g., at beaches downdrift—west—of the Moriches, Shinnecock, and Fire Island Inlet jetties).

In response to sea level rise, existing hard structures will need to be strengthened and elevated repeatedly, and beaches would require additional sand replenishment. The increased costs of retrofitting existing structures or armoring selected portions of the coast may be viable in high population density or high property-value areas of the New York metropolitan area. In some locations, affluent shorefront property owners or seaside communities may also be willing to incur the additional expenses needed to

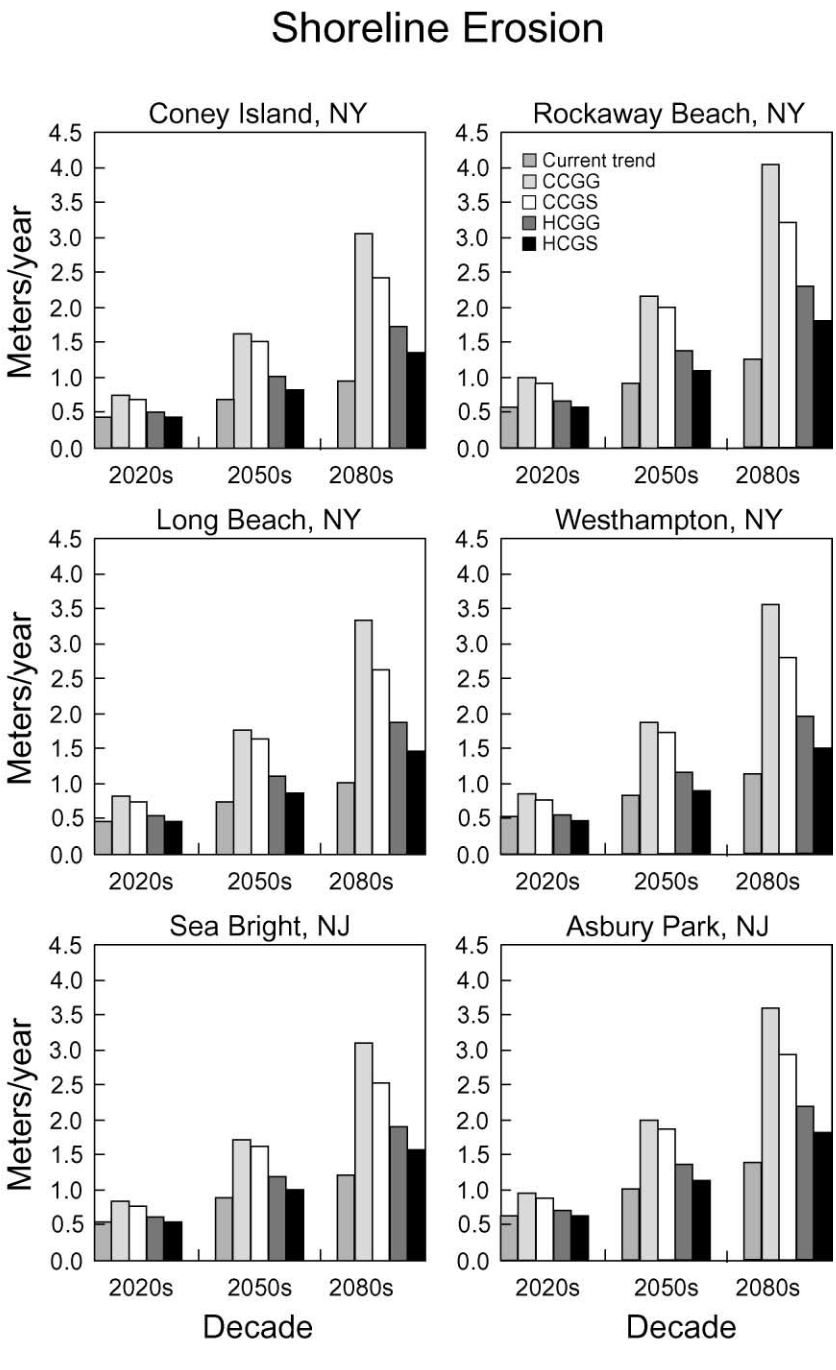

Fig. 8. Rates of shoreline erosion, MEC region, (in meters/yr).

save their beaches, as for example, in Southampton and East Hampton, Long Island (Maier, 1998; Section 3.6).

Because of erosion problems associated with hard structures, a soft approach involving dune restoration and beach nourishment has emerged as the preferred

Table 5(a)
Beach nourishment volumes due to sea level rise for the case study sites (in 10^6 cubic meters)

Locality	Scenario				
	Current trends	CCGG	CCGS	HCGG	HCGS
2000–2020					
Coney Island	0.076	0.187	0.156	0.100	0.086
Rockaway Beach	0.184	0.514	0.467	0.223	0.200
Long Beach	0.235	0.599	0.517	0.304	0.262
Westhampton Beach	0.175	0.451	0.393	0.223	0.193
Sea Bright	0.374	0.806	0.698	0.472	0.412
Asbury Park	0.367	0.791	0.699	0.513	0.461
2020–2050					
Coney Island	0.121	0.369	0.347	0.224	0.167
Rockaway Beach	0.611	1.774	1.637	1.113	0.912
Long Beach	0.537	1.483	1.398	0.946	0.747
Westhampton Beach	0.362	1.057	0.941	0.631	0.435
Sea Bright	0.978	2.301	2.134	1.587	1.266
Asbury Park	0.703	1.864	1.734	1.196	0.936
2050–2080					
Coney Island	0.125	0.592	0.396	0.302	0.245
Rockaway Beach	0.864	3.582	2.665	1.636	1.434
Long Beach	0.657	2.559	1.837	1.352	1.090
Westhampton Beach	0.503	2.248	1.780	1.106	0.899
Sea Bright	1.442	4.443	3.422	2.699	2.049
Asbury Park	1.075	3.486	2.594	1.922	1.622

means of shoreline protection (NRC, 1995). Beach dunes act as a major line of defense against wave attack. Since many natural dunes in the MEC region have been destroyed by housing construction and sand mining, they have frequently been replaced by artificial dunes.

Beach nourishment or restoration consists of placing sand that has usually been dredged from offshore or other locations onto the upper part of the beach. Since erosion is ongoing, beach replenishment must be frequently repeated (e.g., Tables 2 and 5(a), (b)).

The US Army Corps of Engineers has spent a cumulative total of \$2.4 billion[4] nationally and \$884 million within the tri-state region on beach nourishment projects since the 1920s.

Over half a billion dollars have been spent in New York State alone (mostly along the south shore of Long Island)—the largest expenditure for any single state (Duke University, Program for Study of Developed Shorelines, 1999). Over \$250 million has been spent to date on our case study sites (Table 2).

Estimates of future beach nourishment needs for our suite of sea level rise scenarios (Table 5(a), (b)) suggest that supplemental sand volumes could probably be accommodated within typical 50-yr project lifetimes, starting now. However, as shown in Figs. 3 and 5, even greater sea level changes could occur beyond the 50-yr planning horizon. By the latter half of the century, an additional 5–26% volume of sand would be necessary (Table 5(a), (b)). Thus, projects may have to design for potentially higher erosion rates and water levels than those experienced until now. The adequacy of onshore/offshore sand resources on Long Island and northern New Jersey to meet future demands may also need to be re-evaluated.

Retreat or pulling back from the shore may become an appropriate option in areas of lower population densities or land values, or in high-risk areas, subject

Table 5(b)
Percentage of total beach renourishment volume due to sea level rise

Locality	Scenario				
	Current trends	CCGG	CCGS	HCGG	HCGS
2000–2020					
Coney Island	4.9	11.4	9.7	6.4	5.5
Rockaway Beach	2.3	6.1	5.5	2.7	2.4
Long Beach	4.8	11.4	10.0	6.1	5.3
Westhampton Beach	3.2	7.9	6.9	4.1	3.5
Sea Bright	4.6	9.4	8.3	5.8	5.1
Asbury Park	5.7	11.5	10.3	7.8	7.1
2020–2050					
Coney Island	5.2	14.4	13.6	9.3	7.1
Rockaway Beach	4.9	12.9	12.0	8.5	7.1
Long Beach	6.5	16.0	15.3	10.9	8.8
Westhampton Beach	4.4	11.8	10.6	7.4	5.2
Sea Bright	8.7	18.3	17.2	13.3	10.9
Asbury Park	8.0	18.7	17.7	12.9	10.4
2050–2080					
Coney Island	5.4	21.3	15.3	12.1	10.0
Rockaway Beach	7.5	25.2	20.0	13.3	11.9
Long Beach	7.8	24.8	19.1	14.8	12.3
Westhampton Beach	6.0	22.1	18.4	12.3	10.2
Sea Bright	10.1	25.7	21.0	17.3	13.7
Asbury Park	9.6	25.7	20.4	16.0	13.8

[4] Adjusted to 1996 dollars.

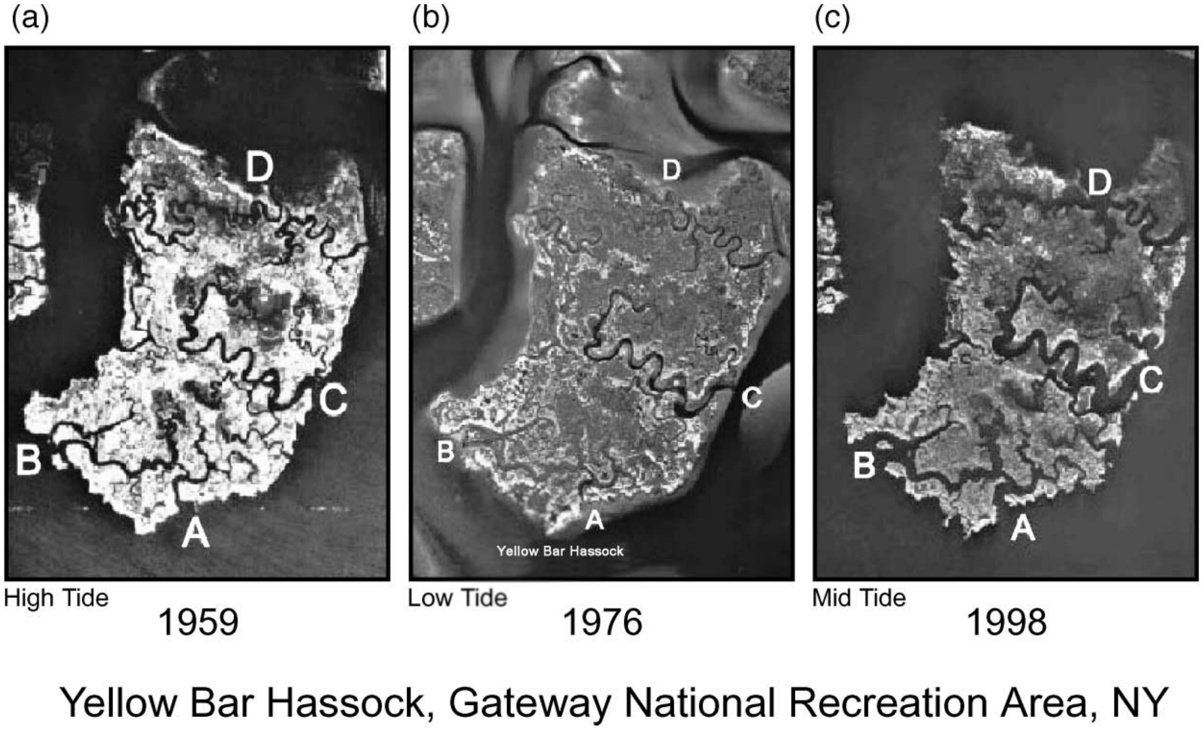

Fig. 9. Aerial photographs of saltmarsh changes, 1959–1998, Yellow Bar Hassock, Jamaica Bay Wildlife Refuge, Gateway National Recreation Area, New York. (a) April 7, 1959, 9:15 am (high tide 7:45 am), (b) March 29, 1976, 12:40 pm (low tide 1:28 am), and (c) March 13, 1998 (mid-tide). Sources: Robinson Aerial Surveys, and AeroGraphics, Bohemia, NY.

to repeated storm damage. The retreat may be gradual, or a sudden abandonment following a catastrophic storm.

A number of US Federal government programs involve the coastal zone. These include the Federal Emergency Management Agency (FEMA) National Flood Insurance Program (NFIP), the NOAA Coastal Zone Management Act (CZMA), the US Department of the Interior Coastal Barriers Resource Act (CBRA), and the Army Corps of Engineers' mandate to provide storm protection, stabilize shorelines, and insure nav-

Table 6(a)
Changes in area (in hectares) at three salt marshes, Jamaica Bay Wildlife Refuge, Gateway National Recreation Area, New York, 1959–1998

Salt Marsh	1959	1976	1998	Percentage of loss since 1959
Yellow Bar Hassock	76.5	70.1	66.8	13
Black Wall Marsh	17.8	17.4	16.6	7
Big Egg Marsh	30.4	30.8	25.9	15
Total area	124.7	118.3	109.4	12 (av.)

Table 6(b)
Changes in area of several selected island salt marshes and a total of more than 15 named island marshes in Jamaica Bay, 1900–1994 (area in hectares)

Single marsh[a]	1900	1974	1994	Percentage of loss since 1900
Nestepol	14.8	2.3	0.24	98
Jo Co	196.4	167.7	151.5	23
Elders Point	48.6	37.7	15.3	69
Fish Kill Hassock	2.0	0.53	0.02	99
Total area marshes (>15 islands)	1274	799	637	50

[a] All measurements are in low marsh, except for Jo Co, which includes both high and low marsh vegetation zones.

Table 7(a)
Surface accretion rates for salt marshes in the New York metropolitan region

State	Salt marsh zone	Accretion rate (mm/yr)	Relative SLR (mm/yr)
CT	low	8.0–10.0	2.6
	high	2.0–6.6	2.6
	high/low	1.8–2.0/3.3	2.2
NY	low	4.0–6.3	2.9
	high/low	5.0/8.0	2.7
	low	2.0–4.2	2.9

Sources: Zeppie (1977), Orson et al. (1998), and Titus (1998).

igability of waterways (NRC, 1990). In particular, NFIP provides flood insurance to communities that adopt and enforce measures to reduce future flood risks in hazardous areas (defined as the 100-yr flood zone, or A-zone; FEMA, 1997). In coastal areas, the V-zone (seaward of the A-zone) consists of the area subjected to at least a 3-ft breaking wave during a 100-yr storm or hurricane. NFIP also calls for designation of erosion zones (or E-zones) and providing setbacks or buffer zones. Several states outside the MEC region have enacted their own setback legislation (Edgerton, 1991).

The Upton–Jones Amendment, enacted in 1987, compensates owners to relocate or demolish buildings in danger of imminent collapse (i.e., located in a zone extending seaward of 10 ft plus five times local average annual erosion rate). New construction would only be permitted landward of the area expected to erode within the next 30 years (small houses) or 60 years (larger buildings). The Upton–Jones amendment is a reasonable approach for responding to immediate coastal hazards (NRC, 1990). However, because only several hundred claims had been filed by the mid-1990s, this program was terminated.

Another way of pulling back is the concept of rolling easement, in which human activities are required to yield to the landward migrating shoreline (Titus, 1998). The state could prohibit bulkheads or other hard structures that would interfere with the shoreline movement. Alternatively, the state could acquire private land when the sea rises by some specified amount. Several states (e.g., New Jersey, Maryland, and Florida) already have acquisition programs for existing coastal hazard areas (Godschalk et al., 2000). These programs could be modified to include the role of future sea level rise and to provide buffer zones for coastal wetlands to migrate landward.

Another approach would be notification or disclosure of potential coastal hazards before property purchase. Several states have such disclosure requirements, including Massachusetts, South Carolina and Texas (Godschalk et al., 2000). Here too, the potential effect of sea level rise could be written into the disclosure document. The California Alquist–Priolo Earthquake Fault Zone Act, although applying to earthquake hazard notification, can serve as a useful precedent.

How and when to arrive at the optimal decision in the face of rising ocean levels is explored by Yohe and Neumann (1997). Several options are given—advanced foresight, wait-and-see, and protect regardless, for three SLR scenarios: 33, 67, and 100 cm by 2100. The first option assumes sufficient advance warning of SLR and fairly rapid market response to the perceived threat. The second option reacts to the imminent loss of property at the time of inundation, while the last option accepts protection as given and simply seeks to minimize its costs. In general, costs for the advanced foresight option are lower than for the wait-and-see option, especially for the two higher SLR scenarios, but this advantage requires more precise knowledge of the course of SLR and effective market-based retreat policy. Costs are highest for permanent protection.

Table 7(b)
Minimum salt marsh accretion rates needed to keep pace with projected mean sea level rise (mm/yr)

Decade	Scenario				
	Current trend	CCGG	CCGS	HCGG	HCGS
2000	2.7	6.4	6.9	4.1	3.5
2010	2.7	8.2	5.3	3.4	2.8
2020	2.7	7.3	3.6	6.0	4.1
2030	2.7	13.3	11.4	5.0	5.6
2040	2.7	6.4	10.8	5.4	2.2
2050	2.7	13.7	6.6	6.4	4.9
2060	2.7	17.5	11.3	7.4	6.2
2070	2.7	13.0	10.5	8.1	5.7
2080	2.7	19.0	22.7	6.2	6.9

Sea level data are for New York City (The Battery; see Table 4 and Fig. 3).

Implementing a rational and equitable strategy for coastal retreat from high-risk zones and additional protection for endangered wetlands will be difficult and politically unpopular. Pressures arising from stakeholders' diverse interests will probably intensify as shorelines shrink and land is inundated (e.g., Figs. 6 and Fig. 7a–d). Adaptation to changing coastal conditions will require the cooperation and coordination of various disparate groups.

6. Summary and conclusions

Anticipated sea level rise, stemming from global climate warming, will affect the coastal zone of the Metropolitan East Coast Region through permanent inundation of low-lying areas—particularly coastal wetlands, acceleration of beach erosion, and greater frequency of flooding episodes. The reduction in the flood return period is very sensitive to small increases in sea level. This will occur regardless of any changes in storm patterns. Another serious impact could be the loss of coastal wetlands and their associated ecological resources.

Observational records of both nor'easters and hurricanes striking the northeast show pronounced interdecadal variability, but no secular trends (Dolan and Davis, 1994; Landsea et al., 1999). On the other hand, increases in coastal flooding that accompany historic sea level rise illustrate how rising ocean levels are likely to exacerbate storm impacts (Zhang et al., 1997). Inasmuch as climate model simulations of future cyclone behavior differ considerably, further research in this area will need to be undertaken. Calculations presented in this paper assume a fixed storm climatology, however.

Climate-induced sea level rise in the MEC area will be enhanced by regional subsidence caused by ongoing crustal adjustments following the last Ice Age. Nevertheless, overall regional sea level rise is expected to remain relatively minor within the next 20 years, ranging between 11 and 30 cm (Table 4; Fig. 3). However, this temporary respite should not induce a false sense of complacency—more pronounced increases could appear by the 2050s (18–60 cm) and especially by the 2080s (24–108 cm).

The sea level rise would lead to more elevated storm floods. The 100-yr floods, ranging between 3 and 3.5 m in the 2020s would rise to 3.1–3.8 m by the 2050s, and 3.2–4.2 m in the 2080s (Fig. 4).

A significant corollary will be the marked reduction in the flood return period. The 100-yr flood within the MEC region would have a probability of recurrence once in 80 to 43 years by the 2020s, 68 to 19 years by the 2050s, and 60 to as often as 4 years, on average, by the 2080s (Fig. 5). The area outlined by the 10-ft contour (3 m) in New York City and environs could have a likelihood of flooding once in 50 to as often as every 5.5 years, on average, by the 2080s (Fig. 5).

A narrow strip of shoreline in the case study sites would be permanently under water, particularly by the 2080s (Table 4 and Fig. 7a–d). However, projected storm floods would cover a more substantial fraction of the test areas after the 2050s (Figs. 4 and 7a–d). More frequent floods, even if storm climatology remained constant, would adversely impact seaside communities, as well as major urban transportation arteries, including highways, rail and air transportation (Fig. 6).

Rates of beach erosion would double or triple at the case study sites by the 2020s, increasing 3 to 6 times by the 2050s, and 4 to 10 times by the 2080s, relative to the 2000s. To compensate for these losses, we calculate that 2.3–11.5% more sand (by volume) would be needed by the 2020s to offset increased erosional losses due to SLR alone, relative to total sand replenishment requirements from all causes (Table 5(a), (b)). Sand volumes increase by 4.4–18.7% by the 2050s. Thus, periodic sand nourishment will probably remain a viable option through mid-century. By the 2080s, however, replenishment, and associated costs, grows more substantially by 5.4–25.7%.

In response to SLR, armoring of the shoreline will be necessary to protect vital infrastructure, such as entrances to bridges and tunnels, airport runways, and also areas of high population density and property value. However, hard or soft defense measures will not be a practical option for the entire MEC coastal zone. Thus, zoning or land-use policies would need to be established to enable an orderly and equitable pullback from the most vulnerable areas.

This could be accomplished by a number of mechanisms, for example, designation of construction setback lines, removal of buildings or hard structures in imminent danger of collapse, and acquisition of empty inland space so that beaches and wetlands could "roll over" or migrate landward. A related concept is that of the rolling easement, in which human activities yield to the landward shifting shoreline (Titus, 1998). Alternatively, the state could have the right to purchase land when the sea rises by some specified amount.

Although we will probably be able to adjust to the impacts of sea level rise of the next 20 years without major dislocations (Fig. 3), this period of grace should be utilized to prepare for future mitigation and adaptation responses. Educational outreach, beginning with concerned stakeholders and policy-makers, should begin now. This study provides an initial scientific framework to help coastal managers, planners, educators, and other concerned stakeholders develop appropriate policies.

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Appendix A. Characteristics of study sites

	Sites					
	Coney Island	Rockaway Beach	Long Beach	Westhampton Beach	Sea Bright–Ocean Town	Asbury Park–Manasquan
Length (km)	4.75	10.3	12.5	6.4	19.0	14.5
Initial date	1994–1995	1975–1997	2002–2003	1997	1994–1998	1997–1999
Duration (years)	50	25	50	30	50	50
Renourishment cycle (year)	10	3	6	3	6	6
SLR (mm/yr)	2.73	2.73	2.58	2.45	3.85	3.85
Berm height NGVD (m)	3.96	3.05	3.05	2.9	3.17	3.17
Depth of closure NGVD (m)	– 5.18	– 5.18	– 6.10	– 6.70	– 6.40	– 6.10

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